IN-34

169431

p.24

Comparing the Results of an Analytical Model of the No-Vent Fill Process With No-Vent Fill Test Results for a 4.96 m³ (175 ft³) Tank

William J. Taylor and David J. Chato
Lewis Research Center
Cleveland, Ohio

NASA

(NASA-TM-106018) COMPARING THE
RESULTS OF AN ANALYTICAL MODEL OF
THE NO-VENT FILL PROCESS WITH
NO-VENT FILL TEST RESULTS FOR A
4.96 CUBIC METERS (175 CUBIC FEET)
TANK (NASA) 24 P

N93-27155

Unclas

G3/34 0169431

COMPARING THE RESULTS OF AN ANALYTICAL MODEL OF THE NO-VENT FILL PROCESS WITH NO-VENT FILL TEST RESULTS FOR A 4.96 m³ (175 FT³) TANK

William. J. Taylor[*] and David. J. Chato[*]
NASA Lewis Research Center
Cleveland, Ohio

ABSTRACT

The NASA Lewis Research Center (NASA/LeRC) have been investigating a no-vent fill method for refilling cryogenic storage tanks in low gravity. Analytical modelling based on analyzing the heat transfer of a droplet has successfully represented the process in 0.034 m³ and 0.142 m³ (1.2 and 5.0 ft³) commercial dewars using liquid nitrogen and hydrogen. Recently a large tank (4.96 m³ {175 ft³}) was tested with hydrogen. This lightweight tank is representative of spacecraft construction. This paper presents efforts to model the large tank test data. The droplet heat transfer model is found to overpredict the tank pressure level when compared to the large tank data. A new model based on equilibrium thermodynamics has been formulated. This new model is compared to the published large scale tank's test results as well as some additional test runs with the same equipment. The results are shown to match the test results within the measurement uncertainty of the test data except for the initial transient wall cooldown where it is conservative (i.e. overpredicts the initial pressure spike found in this time frame).

INTRODUCTION

The economic benefits associated with the development of reusable, space based orbit-to-orbit transfer vehicles (STV) are frequently touted by NASA and the aerospace engineering community. One of the technical challenges in making STVs a reality is the development of a low-g cryogenic propellant resupply capability. Recent analytical and experimental accomplishments as well as planned future experimentation are leading the way in the development of this key, enabling technology.

The no-vent fill transfer method has been chosen for emphasis within the technology program, due to its potential applicability to a wide variety of future spacecraft and perhaps more importantly, it will minimize required orbital operations in comparison with liquid transfer techniques requiring a controlled, local acceleration environment. The no-vent fill technique actually involves two distinct operational phases; tank chilldown with controlled venting of vapor only and subsequent tank filling without venting; thus, precluding venting liquid.

NASA/LeRC is pursuing an ongoing investigation of the no-vent fill process to gain practical experience that will enable the use of this technique in orbital operations. This investigation has focused on both the development of analytical models for simulating the process in conceptual designs and the practical demonstration of the method in an extensive ground test program. The analytical models and the test

---

[*]Member AIAA

experience are both precursors for eventual low-g experimentation.

This paper will present two analytical models of the no-vent fill process, one based on droplet heat transfer and the other on equilibrium thermodynamics. It will present recent test data from no-vent fills of a 4.96 m^3 (175 ft^3) with liquid hydrogen using two different spray systems (Top and bottom) and variety of inlet and starting conditions. It will compare the two models to the data and show that the equilibrium model is the better approach for both spray systems over all conditions tested.

ANALYTICAL MODELS

The analytical models of the no-vent fill process being developed at LeRC are to evolve into predictive design tools. The models should allow the maximum pressure of the receiver tank to be predicted with reasonable accuracy (± 10%) based on a minimum set of inputs. The models are intended to allow parametric tradeoff studies of the no-vent fill process to be performed. Tradeoff studies could examine the receiver tank maximum pressure and therefore the tank weight for different inlet parameters versus the cost and operations required to achieve the inlet conditions.

Two analytical models of the no-vent fill process were used in attempting to predict the receiver tank behavior. The first model (NVFIL) treats the bulk liquid and vapor as separate entities exchanging mass and energy, but not necessarily at equilibrium with each other. The tank wall is also modeled as a separate node in this model. The second model assumes the tank contents are in thermodynamic equilibrium.

NVFIL Model

The NVFIL model of the no-vent fill process for top spray fill configurations has been under development[1,2,3,4] at NASA/LeRC for some time. Detailed discussion of this model can be found in Refs. 1, 2, and 4. The model uses a correlation presented by Brown[5] to calculate the convection coefficient between the spray droplets and the ullage and assumes there is no heat transfer at the interface between the ullage and the accumulated bulk liquid. While there are several input variables for the model, the inputs of primary importance are the liquid inlet temperature, the initial average wall temperature and the liquid inlet mass flow rate. The results from this model have been compared with the test results from 0.034 m^3 and 0.142 m^3 (1.2 ft^3 and 5.0 ft^3) dewars[3,4] and were quite successful in replicating the pressure response of those previous tests.

Equilibrium Model

The thermodynamic equilibrium model is much simpler. The primary assumptions incorporated in the model are: no liquid accumulation takes place prior to the tank wall being chilled to the temperature of the incoming liquid; and once liquid has started to accumulate, the liquid and vapor are in thermodynamic equilibrium. The model performs an energy balance on the tank and its fluid contents for a series of explicit time steps. Starting with the specified initial conditions; e.g., liquid inlet temperature, liquid inlet mass flow rate, tank pressure, tank wall temperature, tank mass to volume ratio, tank wall material specific heat; the model calculates the total fluid mass and the internal energy of the tank contents. The fluid density and enthalpy are calculated by the GASP program[6], based on the current tank pressure. The model then iterates the tank pressure until the fluid qualities based on the density and enthalpy converge. The requisite parameters are then updated and the program proceeds to the next time step. This process continues until either the desired volumetric fill level is attained, or the maximum allowable tank pressure is exceeded, or the program time limit is reached.

2

EXPERIMENT DESCRIPTION

Recently, tests have been conducted with a large (175 ft³) tank at NASA/LeRC's K-Site facility[7]. These tests demonstrated the impact of varying critical input parameters, such as the liquid inlet mass flow rate and the initial tank wall temperature, on the no-vent fill process. Six no-vent fill tests with a top spray liquid injection configuration and five tests with a bottom spray liquid injection configuration were selected for comparison to the analytical model. The selection criteria were a final fill level in excess of 90% and a reliable measurement of the incoming liquid temperature. A detailed description of the test facility is found in reference 7. Key features of the testing relevant to this paper are presented below.

Facilities

The no-vent fill tests were conducted at the LeRC Plum Brook Station Cryogenic Propellant Tank Facility (also known as K-Site). This facility combines a capability for safely handling liquid hydrogen with the vacuum required for multilayer insulation systems. Figure 1 is a simplified system schematic of the test facility as configured for the current test series.

A cryoshroud was installed inside the chamber to provide a uniform heat transfer environment. During the tests it was filled with liquid nitrogen to provide a uniform 88.9 K $\pm$5.6 K (160 R $\pm$10 R) radiant environment for the test tank. Mounted on the cryoshroud was a cylindrical coldguard. During testing, the coldguard is filled with liquid hydrogen boiling at near atmospheric conditions. All test tank lines, except the bypass line, pass through the coldguard and all instrumentation leads are thermally shorted to the coldguard. The coldguard minimizes the heat load to the test tank by absorbing the conduction heat transfer from the ambient environment along the test tank lines and instrumentation wires. The shroud and coldguard and the chamber

entry are shown in Fig. 2.

Liquid hydrogen for testing was supplied by a 49.2 m³ (13,000 gallon) roadable dewar located outside the facility building. Prior to testing, the dewar was vented to near atmospheric pressure (roughly 0.011 MPa (1.6 psig)) and maintained there to cool the hydrogen to a uniform saturation temperature throughout the dewar. During the test, the tank was pressurized to the desired transfer head by withdrawing a controlled quantity of liquid hydrogen, feeding it through a vaporization coil located under the dewar, and forcing the resultant gas back into the dewar. Due to the lag between the raising of the tank pressure and the time required for the bulk liquid temperature to rise to the saturation temperature corresponding to the tank pressure, a quantity of subcooled liquid hydrogen was available for transfer.

Experimental Hardware

Test Tank The test tank selected is ellipsoidal with a 2.21 m (87 inch) major diameter and a 1.2-to-1 major-to-minor axis ratio. The two ends are joined by a short 3.8 cm (1.5 inch) cylindrical section. The tank is made of 2219 aluminum chemically milled to a nominal thickness of 0.22 cm (0.087 inches). Thicker sections exist where they were required for manufacturing (mainly weld lands). The tank has a 0.72 m (28.35) inch diameter access flange on the top. The tank has a mass of 149.63 kg (329.25 lb$_m$), and the tank's volume is 4.96 m³ (175 ft³), yielding a mass-to-volume ratio of 30.2 kg/m³ (1.88 lb$_m$/ft³). The tank was originally designed for a maximum operating pressure of 0.552 MPa (80 psia). Prior to the start of testing the tank was requalified by pneumatic test for a maximum operating pressure of 0.345 MPa (50 psia). The tank is covered with a blanket of 34 layers of multi-layer insulation (MLI) made with double aluminized mylar and silk net spacers. Twelve fiberglass epoxy struts support the tank in the support structure. The thermal performance of the tank is documented in Ref. 8.

3

Steady state heat input is 4.66 W (15.9 btu/hr). This performance is more than adequate to insure that the environmental heat leak can be neglected in the analysis of the test data. Figure 3 shows the tank installed in its support structure suspended over the cryoshroud.

Spray Systems Current concepts[9,10] of no-vent fill systems for low-g applications use one or more pressure atomizing spray nozzles to inject the liquid inflow. The two spray systems shown in Fig. 4 are installed in the test tank. One spray system has a single spray nozzle directed upward mounted near the bottom of the tank. This nozzle becomes submerged soon after liquid begins to accumulate in the tank (at a volumetric fill level of approximately 7%). The other spray system uses a cluster of 13 spray nozzles spraying from the top of the tank (13 spray nozzles were selected due to the availability of a commercial spray manifold with this configuration). These nozzles are located in a position such that the spray nozzles are not submerged until a volumetric fill level of 92% is reached.

The flow capacities of each system are sized, within the constraints of commercially available nozzle sizes, to have the same flow rate for the same inlet pressure. Details of the nozzle sizing can be found in Ref. 2. The nozzles were sized to provide roughly 455 kg/hr (1000 lbm/hr) hydrogen at a pressure drop of 0.067 MPa (10 psi).

Instrumentation

Instrumentation for lines external to the test tank are shown on the Fig. 5 schematic. Instrumentation internal to the tank and on the tank wall is shown in Fig. 6.

Flowmeters Turbine flow meters are located at the inlet to each spray system. The range of the turbine meters is from 2.27 l/min to 227 l/min (0.6 to 60 gpm) with an accuracy of ±1/2% of the reading.

Pressure All pressure transducers are mounted outside the vacuum chamber and connected to the measurement taps by 0.64 cm (1/4 inch) or 0.953 cm (3/8 inch) stainless steel tubes. A 0-0.345 MPa (0-50 psia) and a 0-0.690 MPa (0-100 psia) transducer measure tank pressure from a tap in the capacitance probe. During the first test series thermo-acoustic oscillations on this tap limited resolution to ±0.0138 MPa (2 psia). Rerouting the line outside the coldguard eliminated this problem in the second test series. Accuracy for these tests is estimated at ±1/2% full scale.

Tank Internal Instrumentation Internal instrumentation consists of a capacitance level sensor and a rake of temperature and point level sensors. Stainless steel was selected as the material for internal instrument support due to its low thermal conductivity at liquid hydrogen temperatures relative to other metals. The capacitance probe measures liquid fill heights between 0.074 m (2.9 inches) and 1.69 m (66.7 inches) from the tank bottom by measuring the change in capacitance of two concentric stainless steel tubes as the annular space between them fills with liquid hydrogen. Changes in the dielectric constant of hydrogen with pressure prevent the accuracy of the probe from being better than ±1% full scale. Seventeen silicon diode temperature sensors are installed on the rake as shown in Fig. 6. To thermally isolate these sensors they are mounted on G10 micarta cards. Accuracy of these diodes is ±0.28 K (±0.5 R) to 45 R and ±0.5 K (±0.9 R) at higher temperatures.

External Temperatures Silicon diode temperature sensors are used to measure temperature on the plumbing and tank wall: Two such sensors are located just downstream of the turbine flow meters, two are downstream of the spray system inlet valves, four are on the tank wall, four are on the tank fill/drain line, and two are on the tank lid. During the second test series four additional sensors were added on the tank wall, as shown in Fig. 6. These diodes are slightly

4

less accurate than the internally mounted ones; accuracy is ± 0.5 K (± 0.9 R) below 100 K (180 R) and 1% of reading above that 100 K (180 R). Facility systems and tank insulation are instrumented with a variety of PRTs, Type E, and Type K thermocouples selected for the predicted temperature ranges and required accuracy.

TEST PROCEDURE

The generic test procedure followed for all of the tests is outlined below.

Initial Conditions:

-Vacuum < 10^{-5} Torr
-Tank filled with GH_2
-Cryoshroud filled and operating at 88.9 K (160 R)
-Cold guard filled and maintained at 0.124 MPa (18 psia) pressure

Detailed Procedure:

1. Fill or top-off the tank (if partially full from previous test) to insure that tank lid and flange are at or below desired initial temperature

2. Empty the tank by transferring LH_2 to external receiver dewar, close all inlet valves, and begin vacuum pumpdown of tank to < 0.0138 MPa (2 psia).

3. Establish a by-pass flow of sub-cooled LH_2 with supply dewar pressure maintained at 0.31 MPa (45 psia).

4. Allow by-pass line to thermally stabilize (by-pass line temperature reads near 22.2 K (40 R).

5. With the tank internal pressure at < 0.01382 MPa (2 psia), close tank vent and terminate vacuum pumping.

6. Initiate a no-vent fill through the spray nozzle by opening the valve for the nozzle inlet and closing the by-pass valve. Maintain a constant supply pressure throughout the test.

7. Terminate the fill when the 94 percent fill level is reached or when the tank pressure reaches 0.345 MPa (50 psia), whichever occurs first. Depressurize supply dewar and vent it to near atmospheric pressure.

8. Allow the tank to remain locked up and quiescent for one hour following the fill unless pressure exceeds 0.358 MPa (52 psia); the tank must be vented if the pressure exceeds 0.358 MPA (52 psia). Record data throughout this period also.

TEST RESULTS

The results presented herein were obtained in two phases of testing at K-Site. The tests identified as Fill 18, Fill 19, Fill 20, Fill 21, Fill 22 and Fill 23 were performed during Phase 1A of the K-Site testing(reference 5). The tests identified as K251, K2561, K2091, K2227, and K2731 were performed approximately 1 year later during Phase IB of the K-Site Testing. All of the tests achieved volumetric fill levels of 94% or better. The top spray tests were terminated at this fill level because the nozzle cluster becomes submerged at this point and this factor in conjunction with the rapidly decreasing liquid/vapor interface area (due to the tank geometry) causes the receiver tank pressure to increase rapidly. The bottom spray tests were terminated at this point also, due to the decreasing liquid/vapor interface area. The test conditions and resulting receiver tank final pressures are summarized in Table I.

Top Spray Tests

Figures 7 and 8 are plots of the receiver tank pressure, the liquid inlet temperature, the liquid inlet mass flow rate and the volumetric fill level versus time for all six of the top spray tests. The key input

5

parameters investigated in the tests are the liquid inlet temperature, the liquid inlet mass flow rate, and the initial wall temperature. The effect of varying the initial wall temperature is illustrated in Fig. 7, which shows the final pressure increasing as the initial wall temperature is increased, with all three test cases having similar liquid inlet temperatures. The effect of an offset in the average liquid inlet temperature (after the initial transients have died out) can be observed in figure 8 by comparing fills K2091 and K2631. Even though K2631 wall temperature is significantly higher than K2091 it finishes filling at a lower pressure due to its lower average inlet temperature. It appears that it is inlet temperature which is the dominant parameter in determining the final fill pressure. This is to be expected in liquid hydrogen, since the saturation pressure of hydrogen is quite sensitive to temperature (at 20 K the saturation pressure is 0.0935 MPa, at 21 K the saturation pressure is 0.125 MPa). The effect of the liquid inlet mass flow rate can also be seen in figure 8. In Test K251 the inlet flow rate was reduced to approximately 50% of the mass flow rate for the other tests by lowering the pressure in the roadable dewar which supplied the liquid. The pressure history for K251 is similar in shape and magnitude to the other tests. The principle effect of flow rate is to change the time scale. In order to gain further understanding of the test results, tank pressure, instantaneous inlet saturation pressure and a saturation pressure corresponding an average of the instantaneous bulk liquid temperature readings where plotted as functions of time. Figure 9 shows these curves for Test K2091, which is representative of the other tests. The good agreement between the calculated saturation pressure and the test data led to the development of the thermodynamic equilibrium model discussed earlier.

Bottom Spray Tests

The five no-vent fill tests with the bottom spray liquid injection configuration were conducted in the same manner as the top spray tests and demonstrated the same successful fill levels. The plots of the receiver tank pressure, the liquid inlet temperature, the liquid inlet mass flow rate, and the volumetric fill level are presented in Figs. 10 and 11. Bottom spray results are quite similar in trend to the top spray results presented earlier. The most distinct difference is that the initial transient due to wall cooling is less severe. Due to an artifact of the test rig geometry (the bottom spray inlet line was below the level of the bypass line whereas the top spray inlet line was at the same level) slightly better subcooling was obtained for the bottom spray fills

TEST DATA AND ANALYTICAL MODEL RESULTS COMPARISON

Top Spray Tests

Figures 12 through 17 plot the pressure histories obtained from the two analytical models versus the test data for the six top spray tests.

The top spray test results were initially compared with the results from the NVFIL model used previously to model the results of the tests with the two smaller tanks[4]. The agreement between the test results and the model results for the tests with the large tank was poorer than for the previous cases. For the large tank tests, this model overpredicts the receiver tank pressures by a large margin. In examining the analytical results, it was noticed the ullage temperature rises significantly and then gradually cools during the fill process. This indicates the ullage is being compressed and is inconsistent with the actual test results.

The results from the thermodynamic equilibrium model were in much better agreement with the test data, running within 0.0345 Mpa (5 psia) for most cases. The model did over predict the initial pressure spike for the warmer wall cases, but was no worse than the NVFIL model. Even in these cases, after the

6

initial transient was over the model results returned to a pressure which approximated the experimental results. For test K251 (a cold wall test with a very stable inlet temperature) the model results are very close to the test data throughout the test period.

Bottom Spray Tests

The bottom spray test results were only compared with results from the thermodynamic equilibrium model since the NVFIL assumption of a fine mist of droplets is not applicable after the liquid level has submerged the nozzle. The receiver tank pressure histories for the bottom spray tests are plotted in Figures 18 through 22. The agreement between the test data and the results obtained from the analytical model is very good, with the maximum difference between the predicted pressure and the test results being less than 0.0345 MPa (5 psia). The predicted pressures at the final fill levels were within 0.0172 MPa (2.5 psia) of the test results. Additionally, the data trends were consistent between the test data and the analytical results. These results show that process is proceeding at close to thermodynamic equilibrium. The assumption of thermodynamic equilibrium probably holds true because the accumulated bulk liquid was well mixed throughout the fill process.

Sources of Error

There are several sources of error incorporated in the modelling of the no-vent fill process. The accuracy of the test instrumentation is one. A second source is the material and fluid properties used in the models. Another source of error is introduced by approximating the real process based on the reduced test data.

The test instrumentation and the associated accuracies were discussed earlier in this paper, without regard to the implications of these errors. In the case of the liquid inlet temperature, which has

been shown to be the dominant parameter in determining the final pressure in the receiver tank, the temperature measurement has a accuracy of ± 0.5 K (0.9 R). This accuracy translates to a difference of approximately 0.0276 MPa (4 psia) or 14% in the pressure for saturated hydrogen at 22.78 K (41 R). Thus in some cases (i.e., Fill 18, Fill 20, Fill 21, Fill 22, K251, K2227 and K2731), the results from the equilibrium model are within the accuracy band of the test instrumentation.

Another source of error is the evaluation of the tank wall energy content. The initial wall energy is calculated on a mass averaged basis based on the temperatures from the sensors attached to the tank wall. The small number of sensors (4 for first test series, 9 for the second series) results in a crude nodalization of the tank wall for this purpose. Also the calculations use the theoretical value (calculated using the Kopp-Neumann Law) for the specific heat of 2219 Aluminum presented in Reference 11. This data is the best available information, as the specific heat of 2219 Aluminum at cryogenic temperatures is as yet unavailable. All though these may appear serious shortcomings the effect on the overall results is limited. Even in the warmest wall tests the wall energy is small relative to the total energy involved in the fill process (less than 10% of the energy storage capacity available by raising the incoming liquid to the saturation temperature corresponding to the final fill pressure). Totally neglecting the energy stored in a wall at our warmest initial wall temperature is calculated to introduce a difference of 0.0138 MPa (2 psia) in equilibrium fill pressure.

Additionally some errors are introduced in trying to model a real transient process. The models both assume a constant liquid inlet mass flow rate and temperature. The model inputs are the time averaged value of the test data. In the figures showing the test data some of the final pressure transients show the effects of dropping inlet temperature and flow rate.

For example in test K2091 (on figure 8) the tank pressure drops for a while during the end of the fill process as the inlet temperature stabilizes at a slightly lower value than during the start of the fill.

CONCLUDING REMARKS

Based on the work described herein and the ongoing work at NASA/LeRC, it appears that refueling spacecraft is feasible. No-vent fills have been performed in a normal gravity environment with two different liquid injection configurations. Both injection configurations induced sufficient interaction between the liquid and vapor phases in the receiver tank to promote condensation of the ullage; thereby, maintaining the receiver tank pressures at reasonable levels.

Work is continuing on developing analytical models of the no-vent fill process, however the ground work has been laid. A model that assumes the tank contents are at thermodynamic equilibrium during the fill process predicts the test results for both of the tested inlet configurations with good accuracy. The equilibrium model results are independent of the tank geometry and the liquid inlet configuration. Thus the results obtained with this model form a basis for comparing test results obtained for different test conditions and configurations. The success of the model indicates that with adequate mixing, the no-vent fill process can be simulated without resorting to complex heat transfer models.

The repeated success of no-vent fill tests on the ground show that, at least in normal gravity, adequate mixing can be obtained with many different injection techniques. Whether this is true in a low-g environment seems likely but is not yet proven. In order to continue the development and eventual verification and validation of the analytical models data for no-vent fills in a low-g environment will have to be obtained.

REFERENCES

1. Chato, D.J.: Thermodynamic Modeling of the No-Vent Fill Methodology for Transferring Cryogens in Low Gravity. NASA TM–100932, 1988.

2. Chato, D.J.: Analysis of the Nonvented Fill of a 4.96-Cubic-Meter Lightweight Liquid Hydrogen Tank. NASA TM–102039, 1989.

3. Chato, D.J.; Moran, M.; and Nyland, T.: Initial Experimentation on the Nonvented Fill of a 0.14 m^3 (5 ft^3) Dewar with Nitrogen and Hydrogen. NASA TM–103155, 1990.

4. Taylor, W.J.; and Chato, D.J.: Improved Thermodynamic Modeling of the No-Vent Fill Process and Correlation with Experimental data. NASA TM–104492, 1991.

5. Brown, G.: Heat Transfer by Spray Cooling. Institution of Mechanical Engineers—American Society of Mechanical Engineers—Proceedings of General Discussion on Heat Transfer, Sept. 1951, IME, London, England, 1951, pp. 49–52.

6. Hendricks, R.C.; Brown, A.K.; and Peller, I.C.: GASP—A Computer Program for Calculating the Thermodynamic and Transport Properties for Ten Fluids: Parahydrogen, Helium, Neon, Methane, Nitrogen, Carbon Monoxide, Oxygen, Fluorine, Argon, and Carbon Dioxide. NASA TN D–7808, 1975.

7. Chato, D.J.: Ground Testing on the Nonvented Fill Method of Orbital Propellant Transfer: Results of Initial Test Series. NASA TM–104444, 1991.

8

8. Stochl, R.J.; and Knoll, R.H.: Thermal Performance of a Liquid Hydrogen Tank Multilayer Insulation System at Warm Boundary Temperatures of 630, 530, and 152 R. NASA TM–104476, 1991.

9. Merino, F.; Risberg, J.A.; and Hill, M.: Orbital Refill of Propulsion Vehicle Tankage. (GDC–CRAD–80–00, General Dynamics/ Convair; NASA Contract NAS3–21360), NASA CR–159722, 1978.

10. DeFelice, D.M.; and Aydelott, J.C.: Thermodynamic Analysis and Subscale Modeling of Space-Based Orbit Transfer Vehicle Cryogenic Propellant Resupply. NASA TM–89921, 1987.

11. Touloukian, Y.S.: Recommended Values of the Thermophysical Properties of Eight Alloys, Major Constituents and Their Oxides. Thermophysical Properties Research Center, Purdue University, IN, Feb. 1966.

Table I: No-Vent Fill Test Parameters

Test ID	Liquid Inlet	Initial Wall Temperature (K)	Liquid Inlet Temperature (K)	Inlet Mass Flowrate (kg/hr)	Final Pressure (MPa)	Final Fill Percentage
Fill 18	Bottom Spray	21.7	22.2	495.0	0.177	94
Fill 19	Top Spray	104.4	23.0	421.8	0.227	94
Fill 20	Top Spray	126.1	22.4	337.7	0.257	94
Fill 21	Bottom Spray	101.7	22.2	448.6	0.233	94
Fill 22	Bottom Spray	66.7	21.7	505.0	0.187	94
Fill 23	Top Spray	70.0	22.8	419.5	0.210	94
K2091	Top Spray	18.1	23.4	442.2	0.204	94
K251	Top Spray	23.3	21.9	234.0	0.181	94
K2631	Top Spray	86.0	22.3	477.2	0.195	94
K2227	Bottom Spray	17.0	22.0	534.5	0.177	94
K2731	Bottom Spray	87.9	21.9	510.0	0.196	94
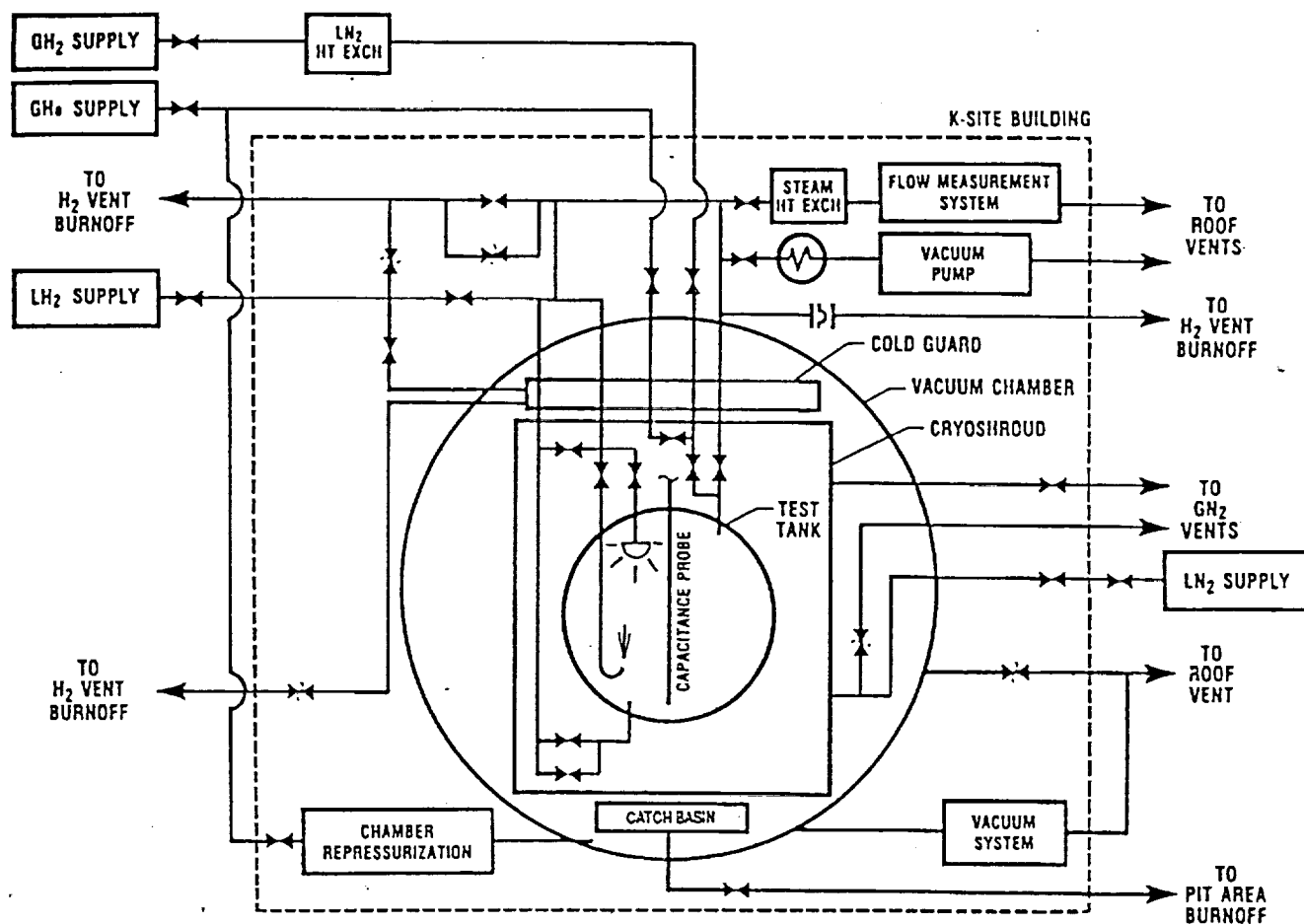
Figure 1. K-Site Simplified Facility Schematic with Research Hardware.
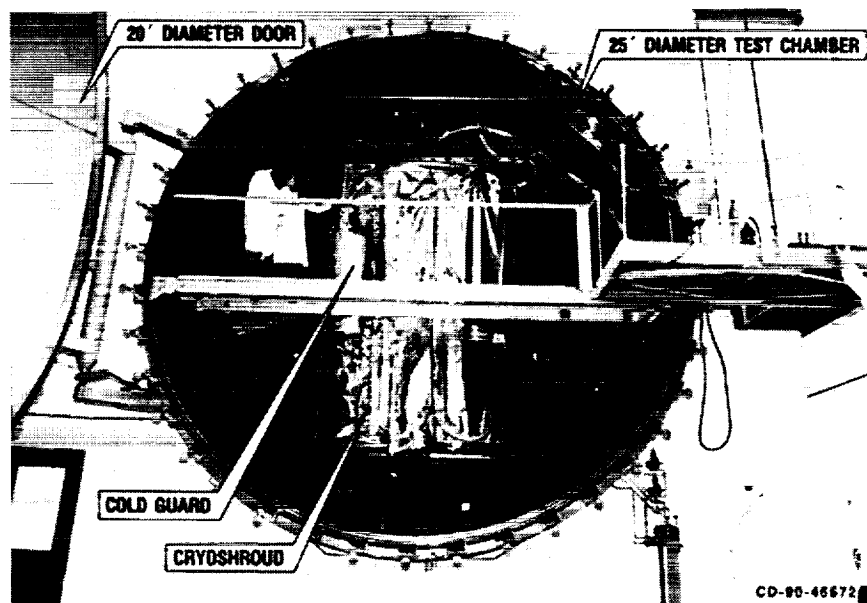
Figure 2. K-Site Vacuum Chamber

11
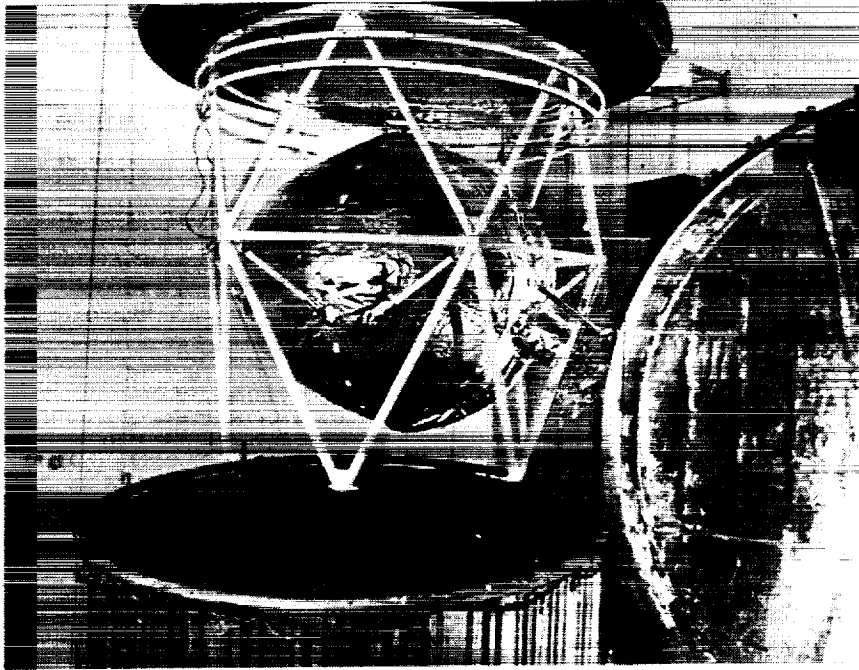
Figure 3. Test Tank Suspended over Cryoshroud

Figure 4. Spray Nozzles

P, ☐P Pressure transducer
P, ☐ΔP Delta pressure transducer
F, ☐8 Turbine flowmeter
SD, ○ Silicon diode temperature sensor
☐ Burst disk

Pnematic valve
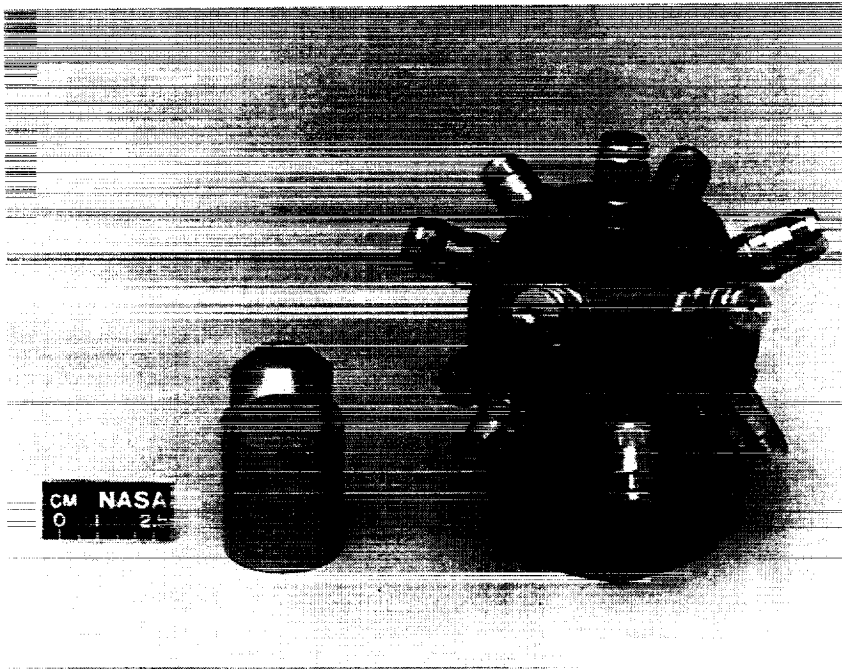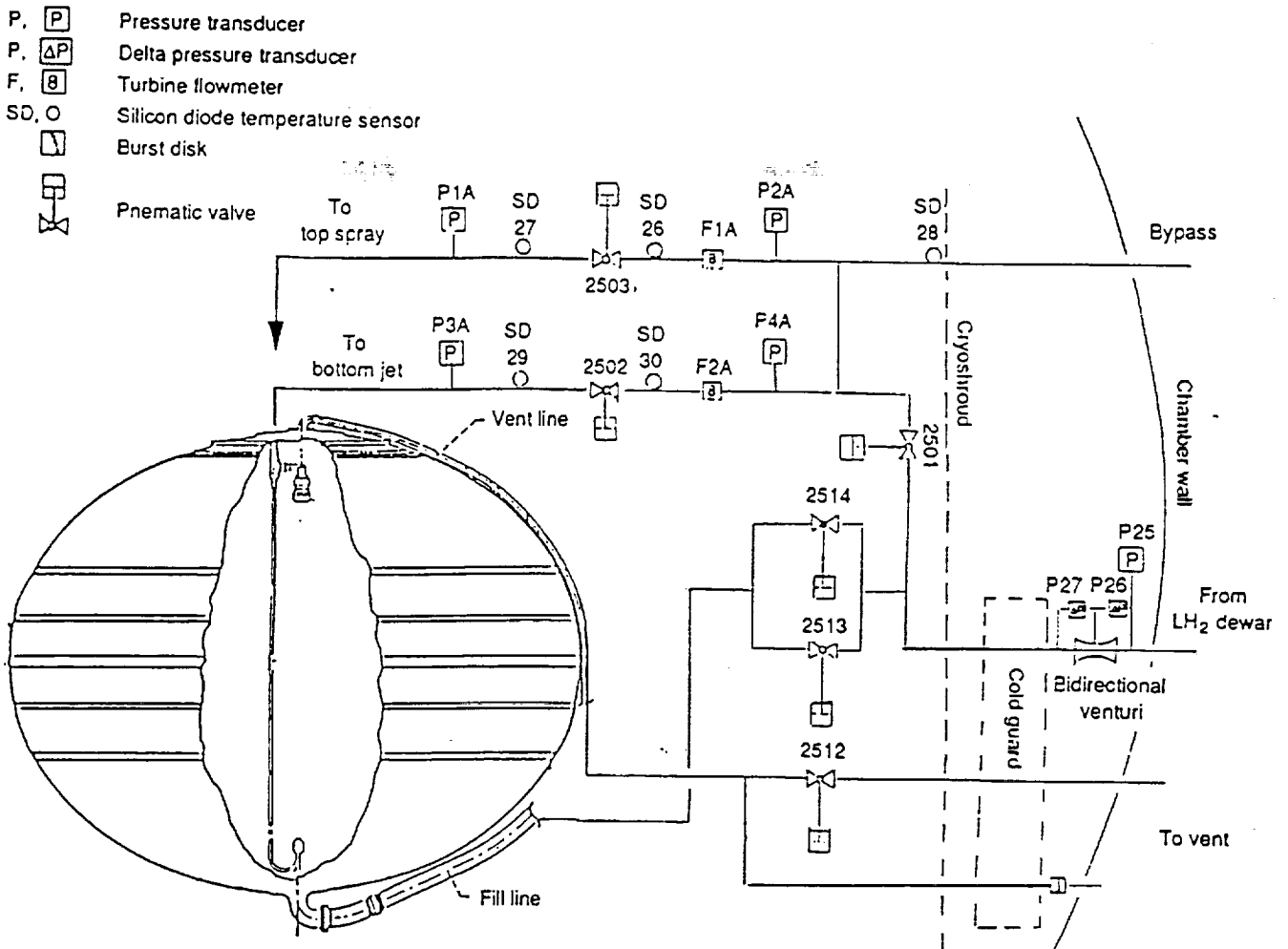
Figure 5. Schematic of Hydrogen Lines in K-Site Vacuum Chamber

Percent

Capacitance probe

These sensors used for second test series only.

● Internal temperature sensors
◆ External wall temperature sensors
■ Close-spaced temperature sensors near liquid-vapor interface
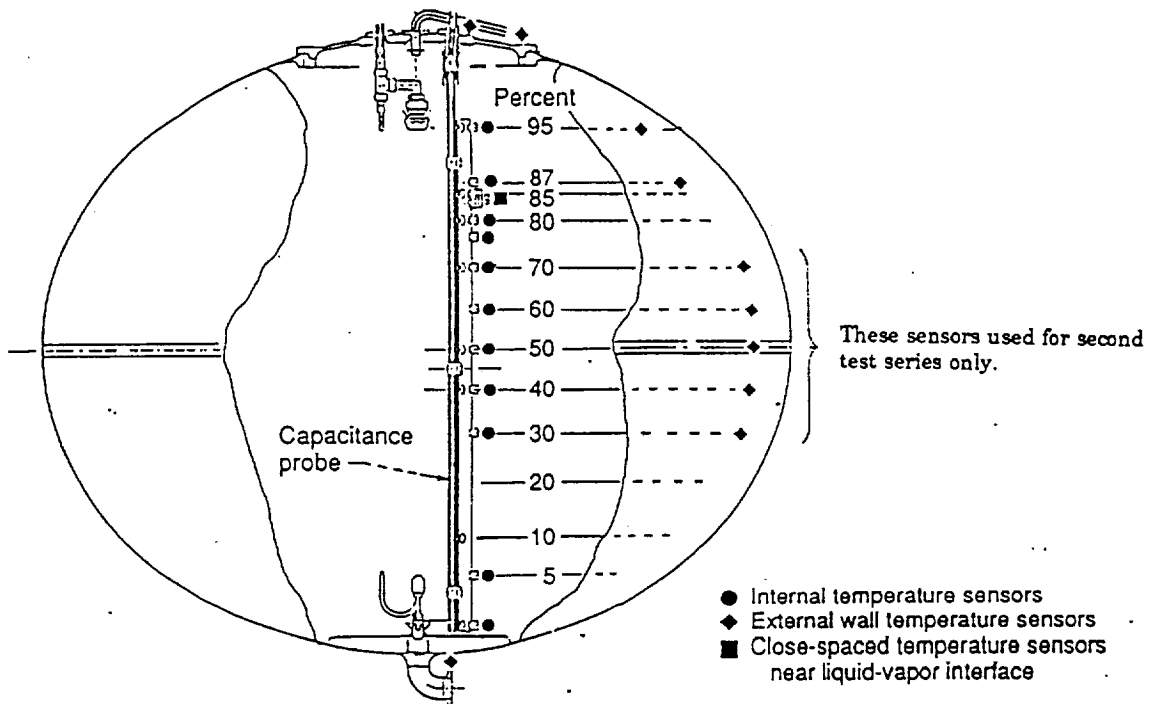
Figure 6. Tank Internal Instrumentation and Wall Temperature Sensors
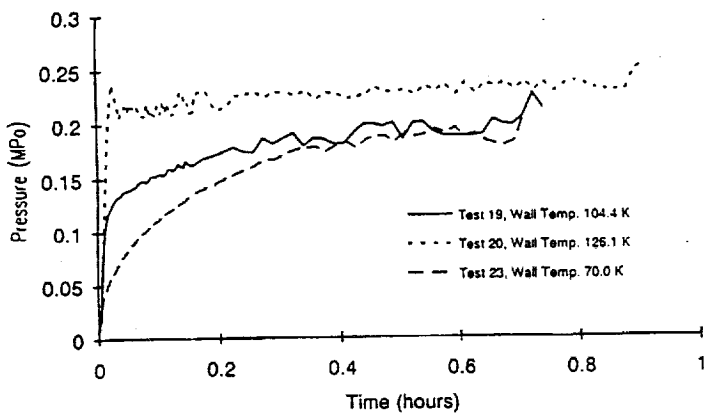
13

a) Tank Pressure History.
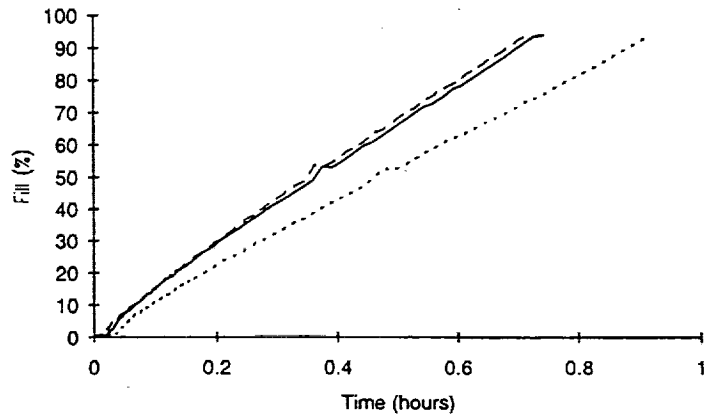
b) Volumetric Fill Level.
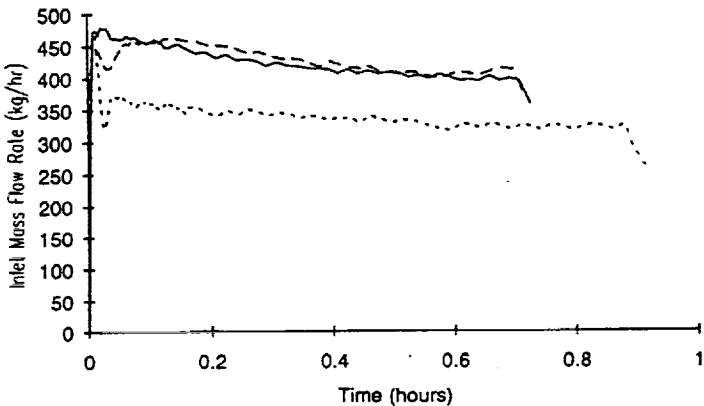
c) Liquid Inlet Mass Flow Rate.
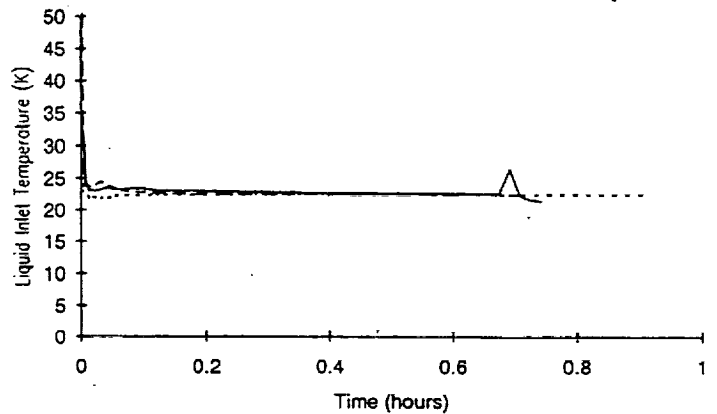
d) Liquid Inlet Temperature.

Figure 7. Tank Pressure Response and Inlet Conditions for Top Spray Tests from First Series
(Showing Influence of Initial Wall Temperature)
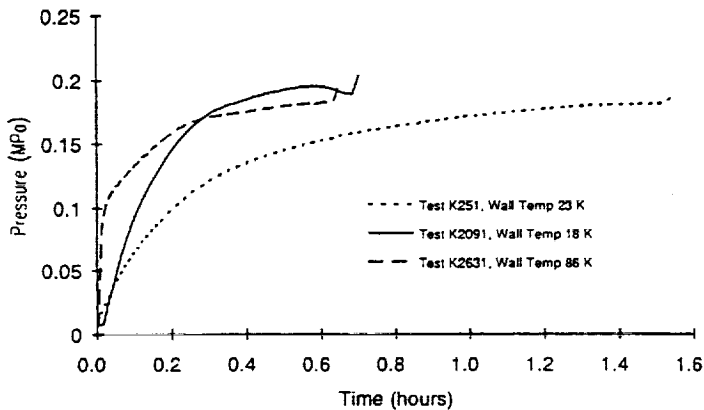
a) Tank Pressure History.
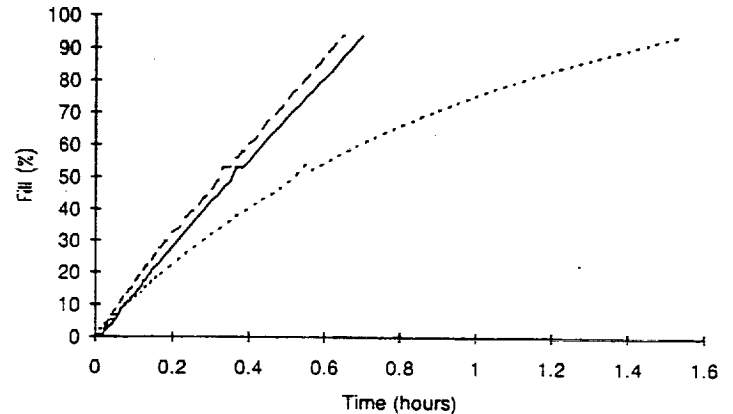
b) Volumetric Fill Level.
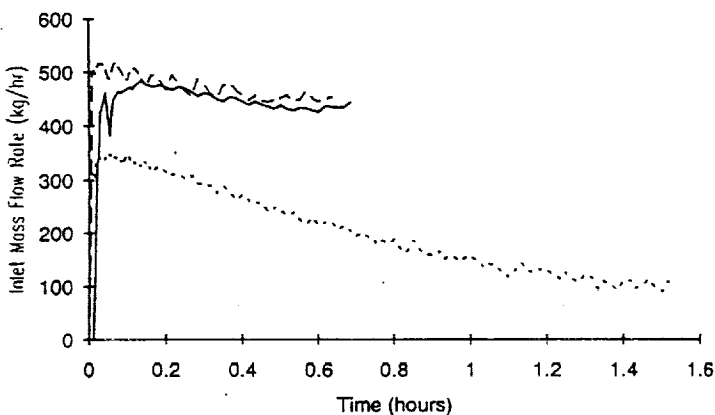
c) Liquid Inlet Mass Flow Rate.
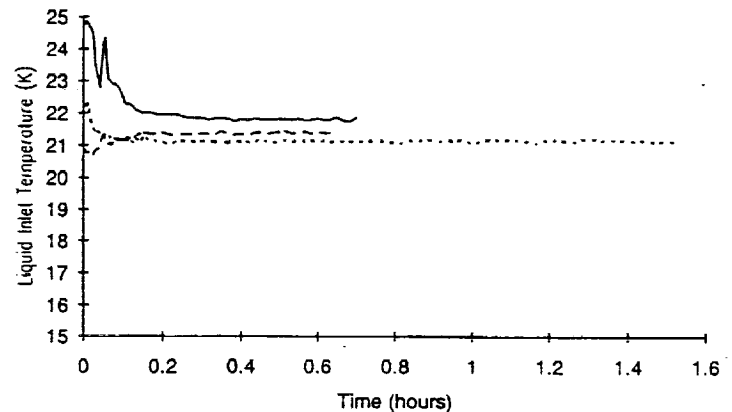
d) Liquid Inlet Temperature.

Figure 8. Tank Pressure Response and Conditions for Top Spray Tests from Second Series
(Showing Effect of Average Inlet Temperature)
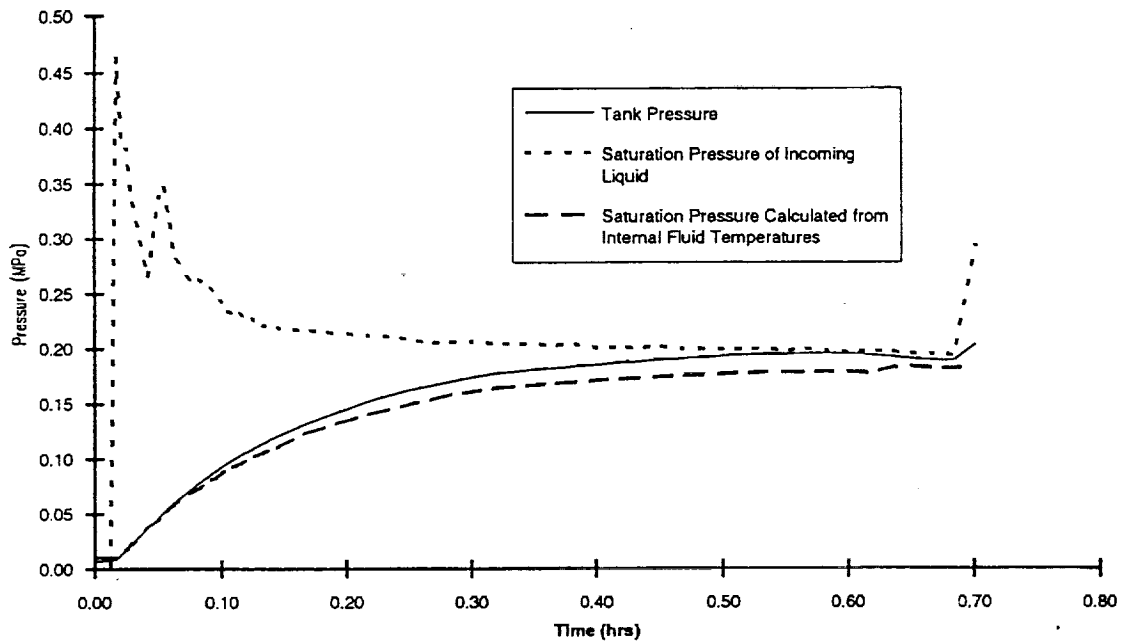
Figure 9. Comparison of Tank Pressure to Calculated Saturation Pressure for Test K2091
(Initial Wall Temperature 18.1 K, Flow Rate 442.2 Kg/hr)

a) Pressure

b) Fill Level

c) Flow Rate

d) Inlet Temperature
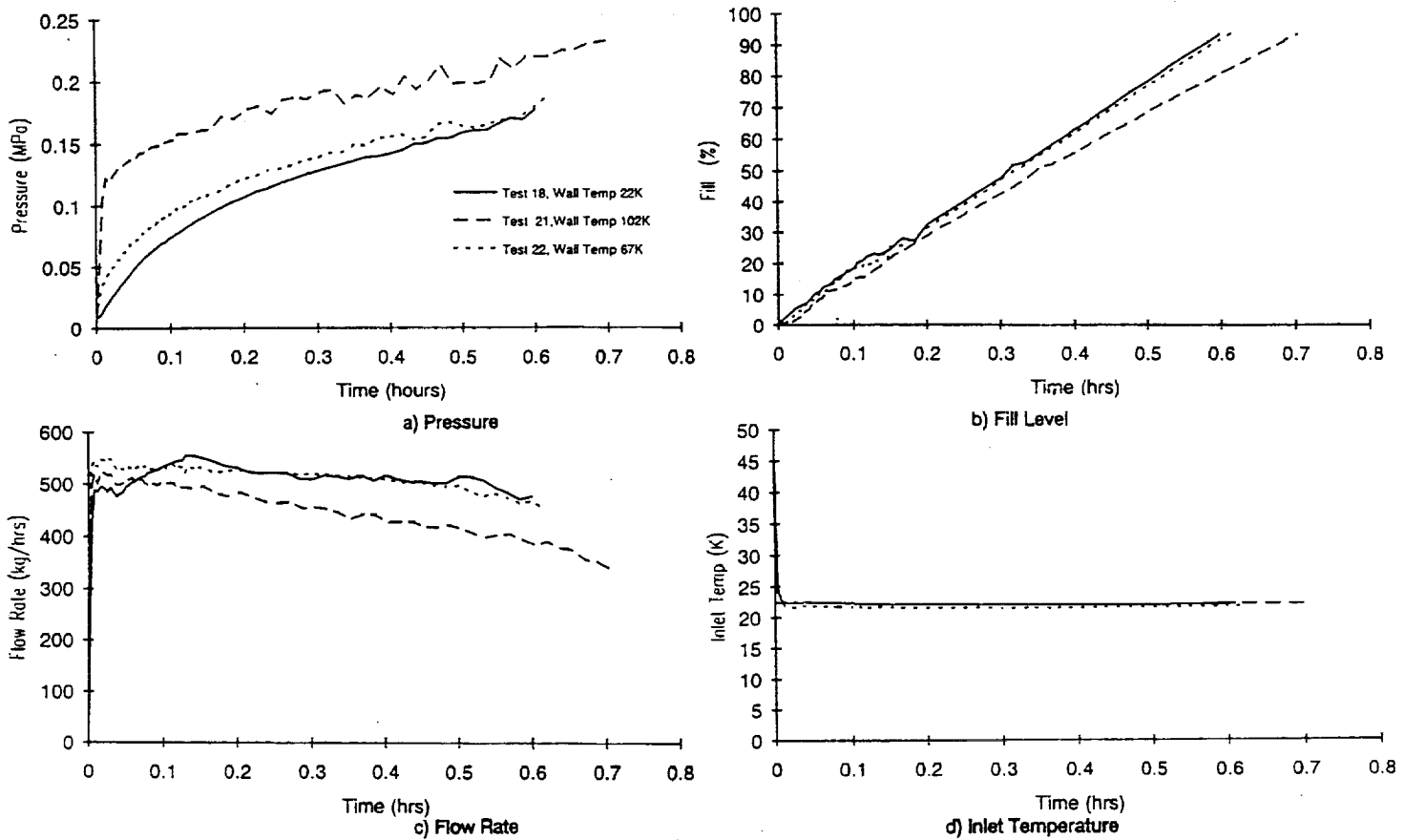
Figure 10. Tank Pressure Response and Inlet Conditions for Bottom Spray Tests from First Series

15

a) Tank Pressure History.

b) Volumetric Fill Level.

c) Liquid Inlet Mass Flow Rate.

d) Liquid Inlet Temperature.
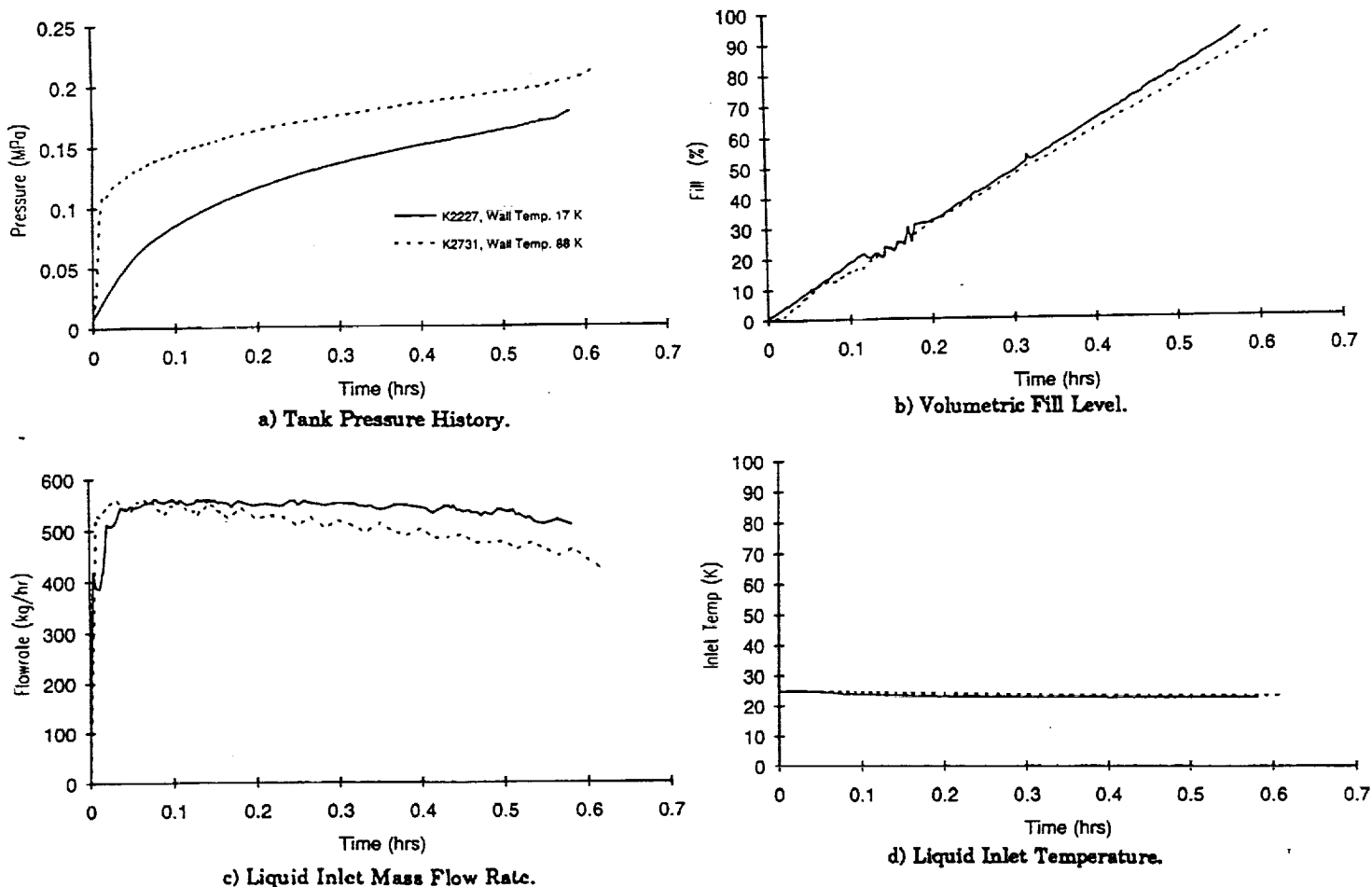
Figure 11. Tank Pressure Response and Inlet Conditions for Bottom Spray Tests from Second Series
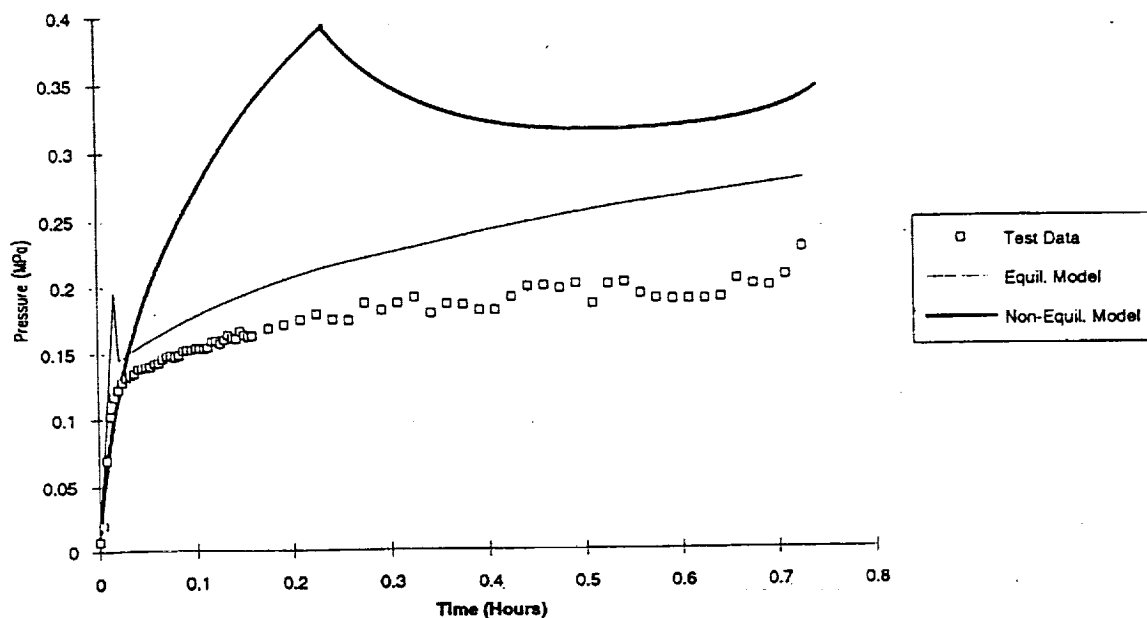
Figure 12. No-Vent Fill Test 19 (Top Spray, Initial Wall Temperature 104.4 K, Average Inlet Temperature 23 K, Flowrate 421.8 kg/hr) Test Data versus Analytical Model Results

16
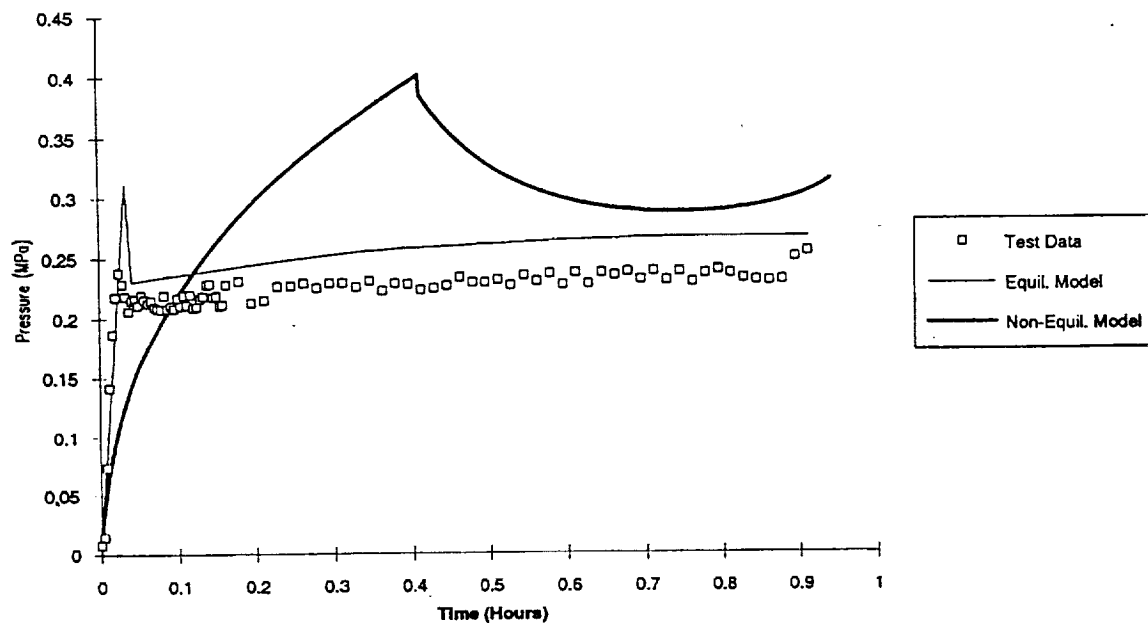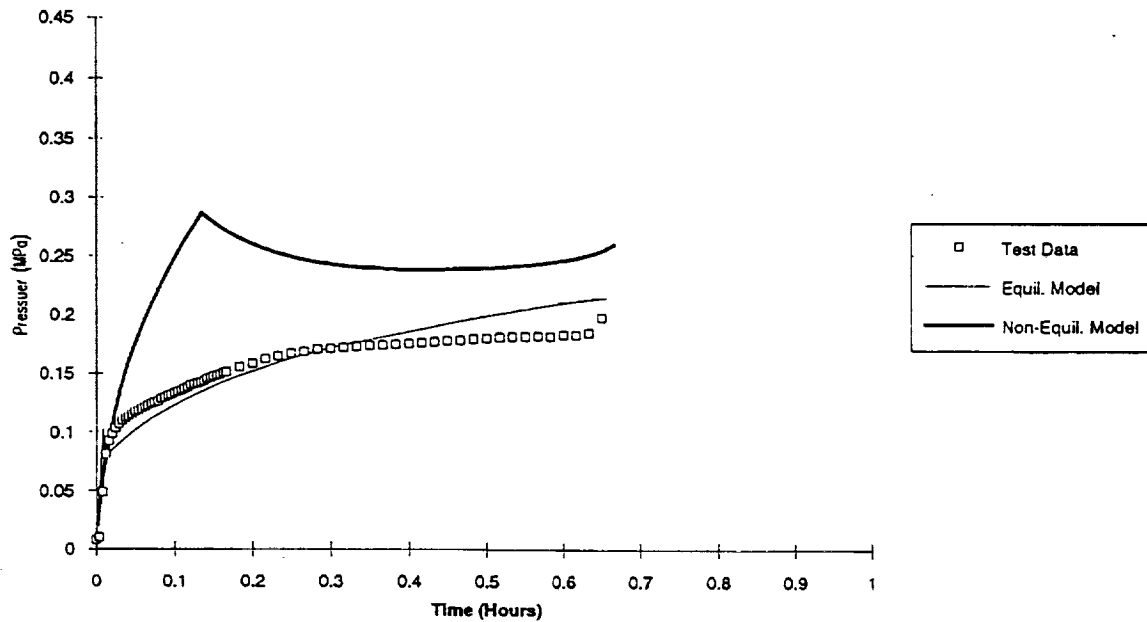
Figure 13. No-Vent Fill Test 20 (Top Spray, Initial Wall Temperature 126.1 K, Average Inlet Temperature 22.4 K, Flowrate 337.3 kg/hr) Test Data versus Analytical Model Results
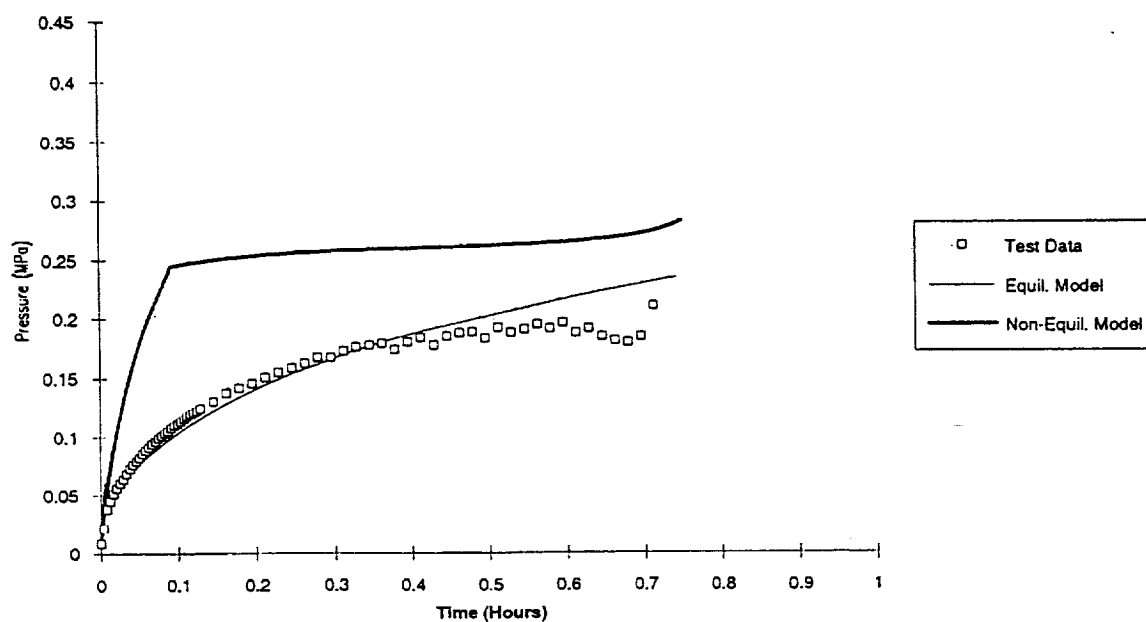
Figure 14. No-Vent Fill Test 23 (Top Spray, Initial Wall Temperature 70.0 K, Average Inlet Temperature 22.8 K, Flowrate 419.5 kg/hr) Test Data versus Analytical Model Results

17
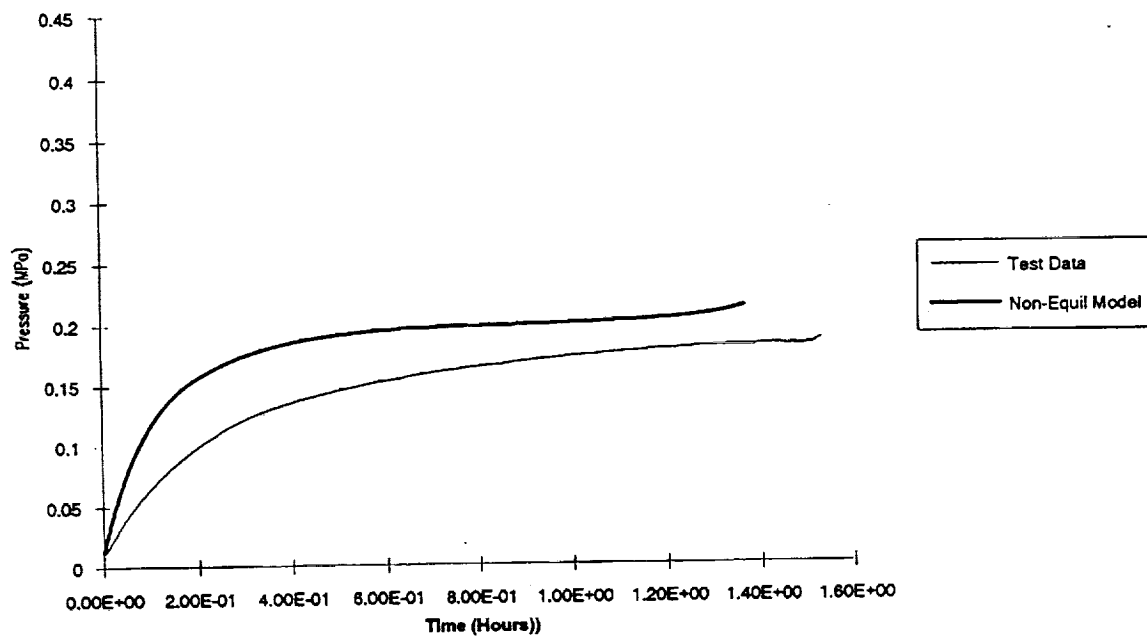
a. Non-equilibrium Model
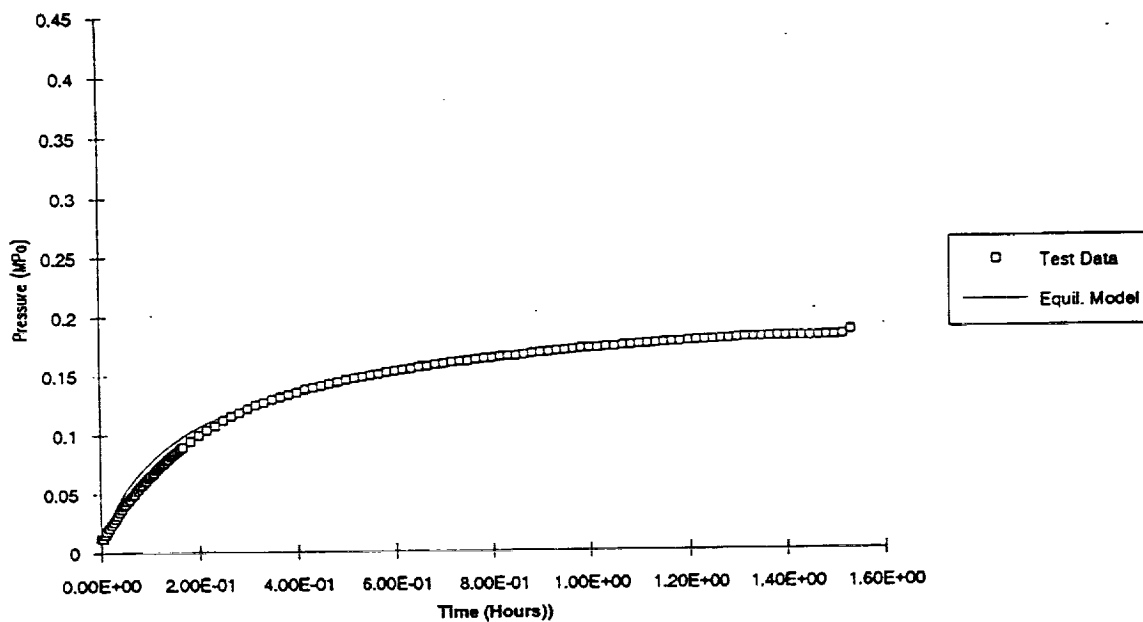
b. Equilibrium Model

Figure 15. No-Vent Fill Test K251 (Top Spray, Initial Wall Temperature 23.3 K, Average Inlet
Temperature 21.9 K, Flowrate 234.0 kg/hr) Test Data versus Analytical Model Results
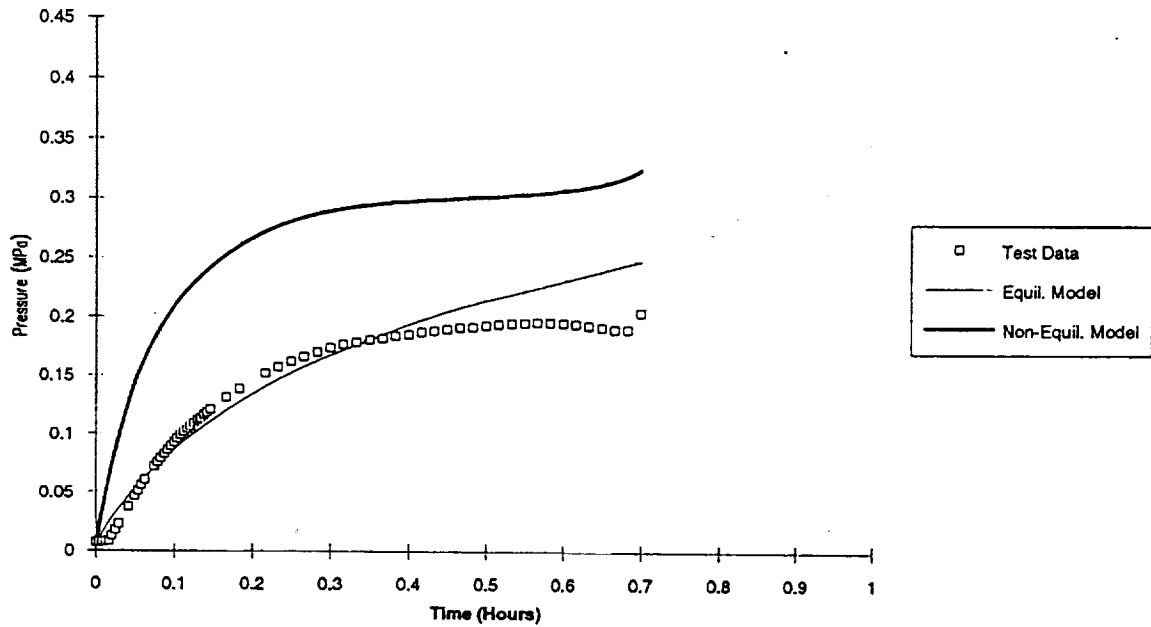
Figure 16. No-Vent Fill Test K2091 (Top Spray, Initial Wall Temperature 18.1 K, Average Inlet
Temperature 23.4 K, Flowrate 442.2 kg/hr) Test Data versus Analytical Model Results

Figure 17. No-Vent Fill Test K2631 (Top Spray, Initial Wall Temperature 86.0 K, Average Inlet
Temperature 22.3 K, Flowrate 477.2 kg/hr) Test Data versus Analytical Model Results
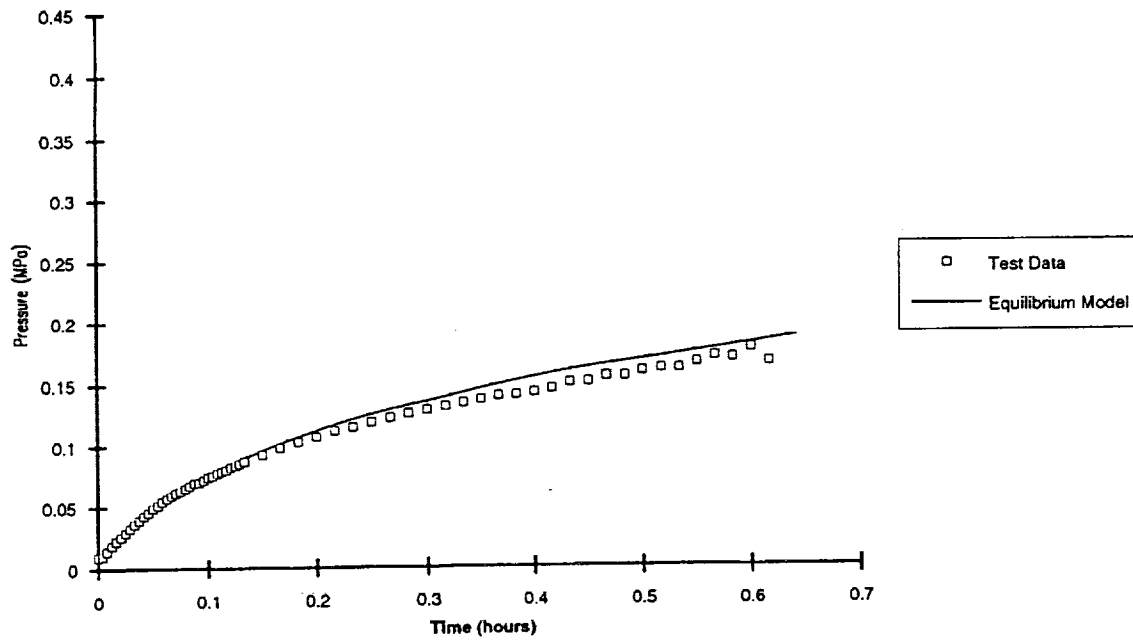
Figure 18. No-Vent Fill Test 18 (Bottom Spray, Initial Wall Temperature 21.7 K, Average Inlet Temperature 22.2 K, Flowrate 495.0 kg/hr) Test Data versus Analytical Model Results
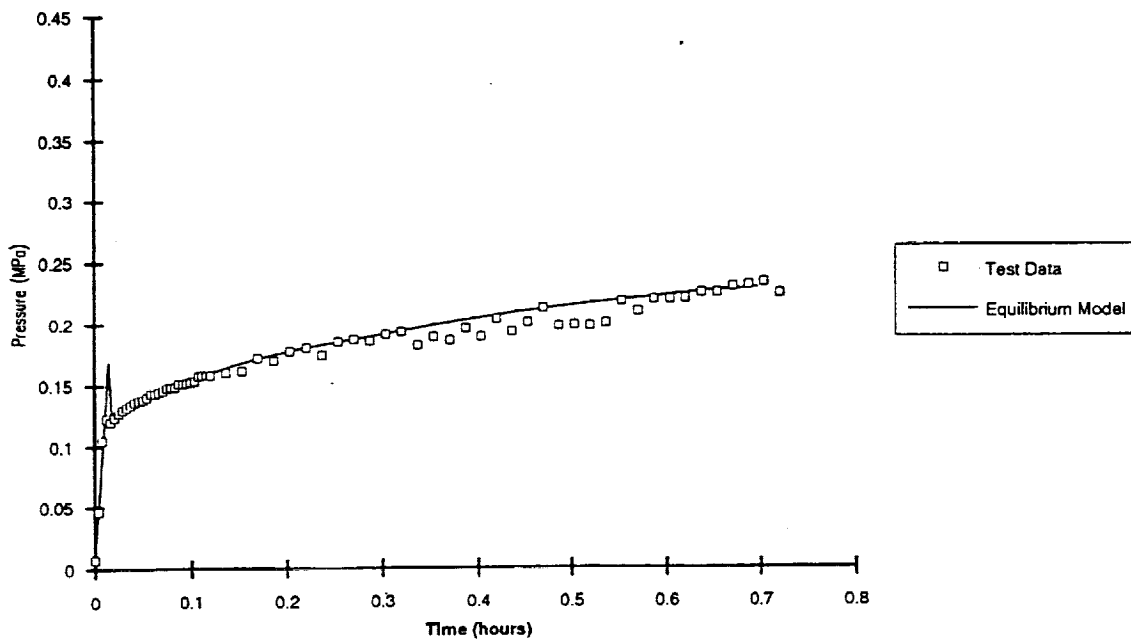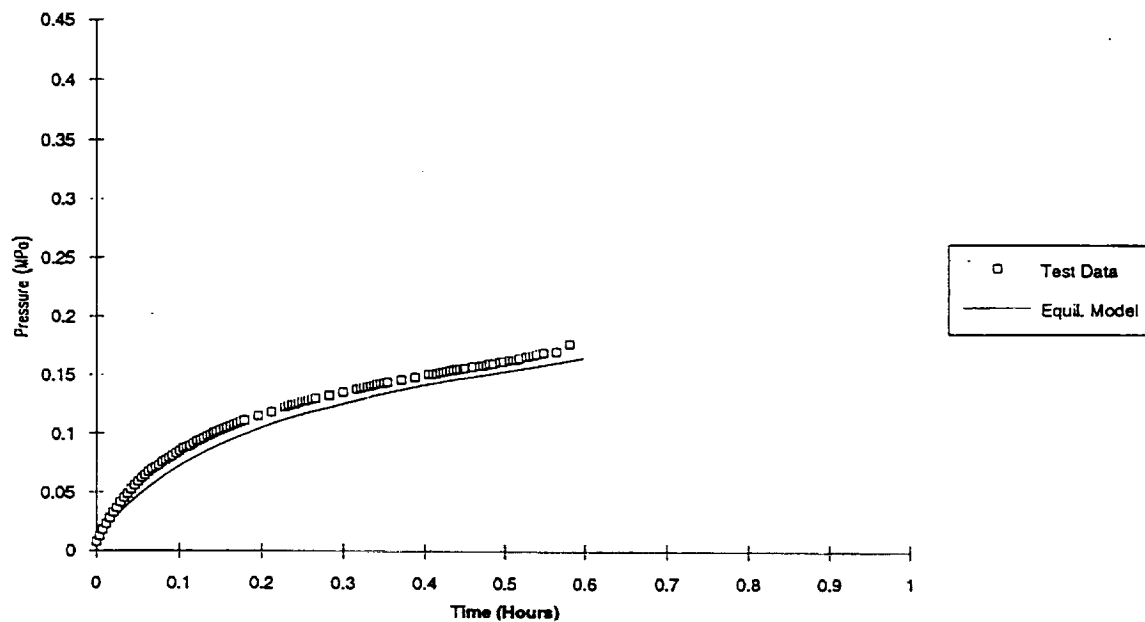

Figure 19. No-Vent Fill Test K21 (Bottom Spray, Initial Wall Temperature 101.7 K, Average Inlet Temperature 22.2 K, Flowrate 448.6 kg/hr) Test Data versus Analytical Model Results

20
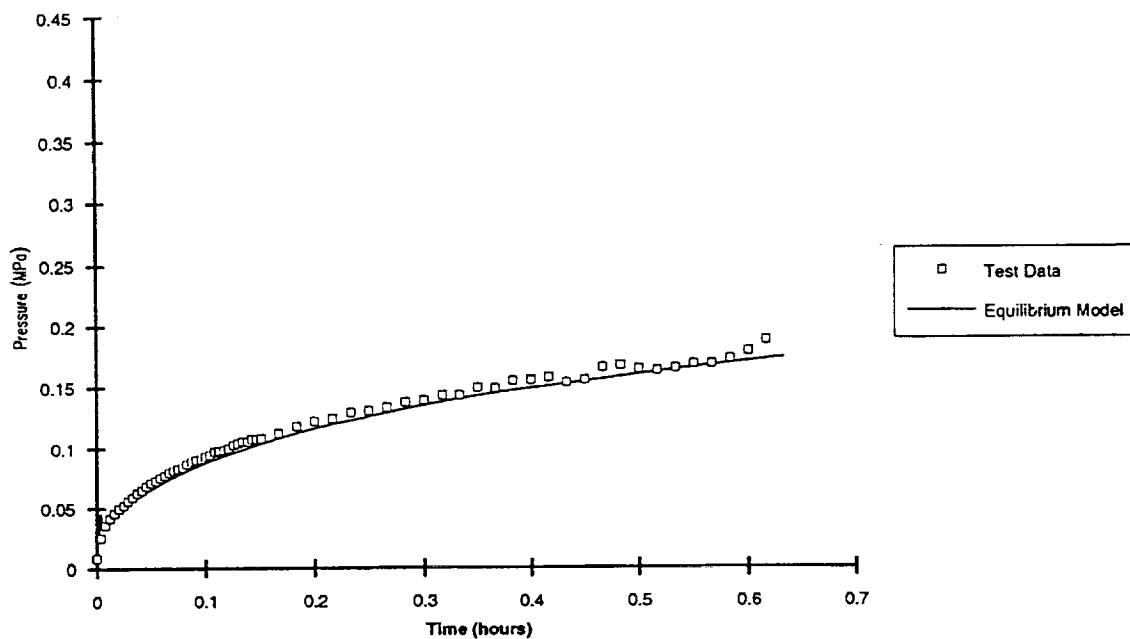
Figure 20. No-Vent Fill Test 22 (Bottom Spray, Initial Wall Temperature 66.7 K, Average Inlet
Temperature 21.7 K, Flowrate 505 kg/hr) Test Data versus Analytical Model Results

Figure 21. No-Vent Fill Test K2227 (Bottom Spray, Initial Wall Temperature 17.0 K, Average Inlet
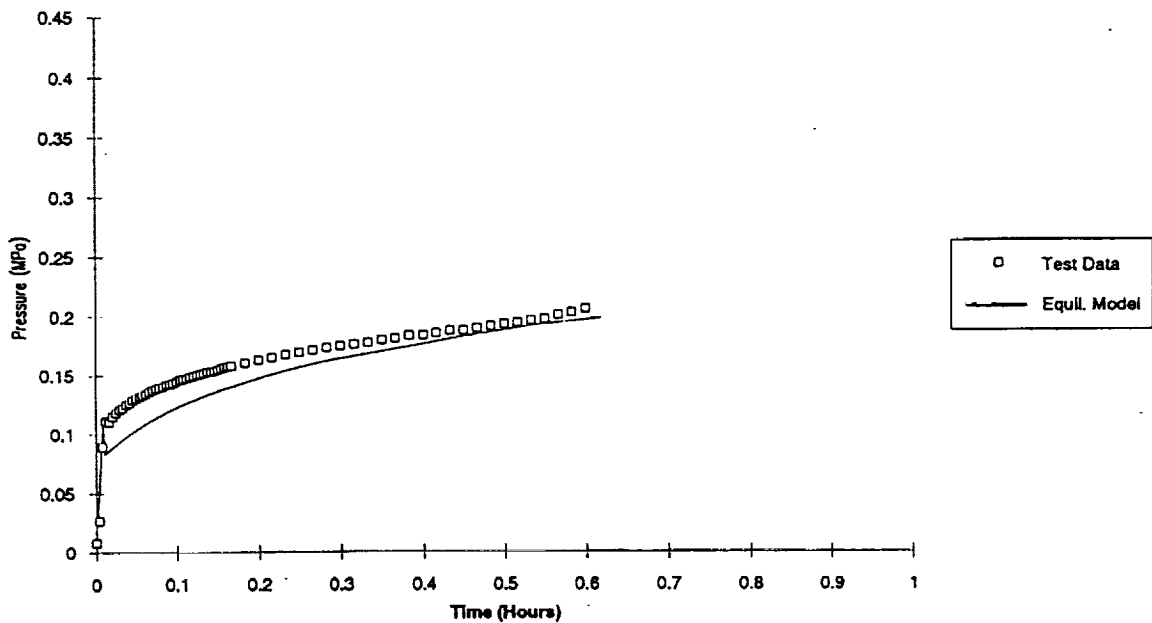Temperature 22.0 K, Flowrate 534.5 kg/hr) Test Data versus Analytical Model Results

21

Figure 22. No-Vent Fill Test K2731 (Bottom Spray, Initial Wall Temperature 87.9 K, Average Inlet Temperature 21.9 K, Flowrate 510.0 kg/hr) Test Data versus Analytical Model Results

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE February 1993	3. REPORT TYPE AND DATES COVERED Technical Memorandum

4. TITLE AND SUBTITLE

Comparing the Results of an Analytical Model of the No-Vent Fill Process With No-Vent Fill Test Results for a 4.96 m^3 (175 ft^3) Tank

5. FUNDING NUMBERS

WU–506–48–00

6. AUTHOR(S)

William J. Taylor and David J. Chato

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–7575

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM–106018

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category 34

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The NASA Lewis Research Center (NASA/LeRC) have been investigating a no-vent fill method for refilling cryogenic storage tanks in low gravity. Analytical modelling based on analyzing the heat transfer of a droplet has successfully represented the process in 0.034 m^3 and 0.142 m^3 (1.2 and 5.0 ft^3) commercial dewars using liquid nitrogen and hydrogen. Recently a large tank (4.96 m^3 {175 ft^3}) was tested with hydrogen. This lightweight tank is representative of spacecraft construction. This paper presents efforts to model the large tank test data. The droplet heat transfer model is found to overpredict the tank pressure level when compared to the large tank data. A new model based on equilibrium thermodynamics has been formulated. This new model is compared to the published large scale tank's test results as well as some additional test runs with the same equipment. The results are shown to match the test results within the measurement uncertainty of the test data except for the initial transient wall cooldown where it is conservative (i.e. overpredicts the initial pressure spike found in this time frame).

14. SUBJECT TERMS

Cryogenics, Liquid rocket propulsion; Propellant transfer

15. NUMBER OF PAGES
24

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT